STUMP-LEVEL ALLOMETRIC MODELS FOR ABOVEGROUND DENDROMASS OF TWO COPPICED BLACK POPLAR CLONES IN SOUTH-WESTERN BULGARIA

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Abstract

The main objective of this study was to derive clone-specific stump-level biomass models for coppiced plants of the black poplar (Populus × euroamerica) hybrids ‘Agathe’ and ‘Guardi’, grown in South-western Bulgaria, which provide robust estimates of the aboveground dendromass from various sets of tree- and stand-level predictors.

We used as principal predictor variables the measurements of the main shoot on the stump - total height, basal and breast-height diameters and we applied the method of conditioning in order to expand the models with an additional (secondary) predictor. Spacing, root age, shoot age and number of shoots per stump were considered as additional independent variables.

Four and three best models, which included either root age or number of shoots, were selected for clones ‘Agathe’ and ‘Guardi’, respectively. The best three-predictor equations were based on the product between main shoot height and basal diameter of the main shoot, while the best two-predictor regression models involved either basal or breast-height diameter of the main shoot. They explained more than 80% of the variation in the aboveground lignified biomass of the investigated genotypes. The models are applicable for estimation of the leafless biomass of coppiced plants from these poplar clones, grown at various densities in the transitional Mediterranean climate of south-western Bulgaria and harvested within five years of stump age.

Key words: biomass equations, Nelder wheel design, Populus × euroamerica ‘Agathe’, Populus × euroamerica ‘Guardi’

INTRODUCTION

Energy crops are short-rotation, high-density systems of selected genotypes (Ceulemans, Deraedt, 1999), which are intended for production of biomass and which are usually managed by repeated Coppicing. Poplars are among the most appropriate species for such mode of cultivation due to their fast growth and ability to sprout. Populus × euroamerica ‘Agathe’ is a female black poplar hybrid described as a very perspective cultivar for wood production, possessing high ecological plasticity and long growth period (Tsanov, Mikov, 1997). The potential of Populus × euroamerica ‘Guardi’ for cultivation in short-rotation plantations, due to its fast initial growth, has been recognized and it has been described as a cultivar of the future, because of its ability to
succeed in relatively adverse growth conditions (Tsanov, Mikov, 1997). These ecological and biological peculiarities of the clones ‘Agathe’ and ‘Guardi’ determine their importance for establishment of poplar energy plantations in the transitional Mediterranean climate of south-western Bulgaria plains.

Cultivation of short-rotation crops usually involves estimation of the total lignified biomass production, which is based on individual plant mass and plantation density. Biomass equations relate tree biomass (kg) as well as its components, with easily measured tree and stand variables and to achieve acceptable accuracy the tree-level predictors normally will vary with tree form. Beside the typical single-stem tree form, the shape of the woody plant can also be characterized by shrub-like form, which is pertinent to bushes, but also to coppiced plants. The predictor variables for biomass estimation of shrubby forms with multiple stems often include diameter at root collar, total height, number of stems and perhaps crown width (Burkhart, Tomé, 2012).

However, very few biometric models derived for shrubs or coppiced plants take the peculiarities of the tree shape into account. Very often, the general allometric equation (Huxley, 1972), relating the dry biomass weight to a power function of tree diameter, is applied regardless of the tree form (Paul et al., 2013a, b). The usual procedure for coppiced plants, grown in energy crops, is to derive the general allometric equation at shoot level and to apply it separately for each shoot on the stump (Laureysens et al., 2003; Walle et al., 2007; Paris et al., 2011; Verlinden et al., 2015). The tree diameters used in such cases are usually at lower height above ground, such as 22 cm, 30 cm and 100 cm, because of the small plant size. Allometric models at stool level are known for coppiced chestnut trees in Spain (Menéndez-Miguélez et al., 2013). To derive the models, the examined predictor variables included diameter of the thickest shoot and its height, number of shoots per stool, arithmetic mean stool diameter, quadratic mean stool diameter and stool basal area. Stump-level allometric models have been developed also for 4 juvenile black poplar clones, grown in Northern Bulgaria (Stankova et al., 2016), for 11 poplar cultivars in an experimental plantation in northern Spain (Valbuena-Castro et al., 2016) and for 6 poplar clones in central-northern Spain (Oliveira et al., 2017). The models employed as principal predictors the length and the basal or breast-height diameter of the main shoot, together with the number of the shoots on the stump. The studies recognized also the importance of spacing (Stankova et al., 2016) and plant age (Valbuena-Castro et al., 2016; Oliveira et al., 2017) as other possible independent variables that can increase the predictive power of the dendromass models at stool level.

The main objective of this study is to derive clone-specific stump-level biometric models for coppiced plants of the black poplar hybrids ‘Agathe’ and ‘Guardi’, grown in south-western Bulgaria, which will allow robust aboveground dendromass estimation from various sets of tree- and stand-level predictors.
MATERIALS AND METHODS

Experimental plantation and data collection

Experimental plantation with black poplar hybrid clones ‘Agathe’ and ‘Guardi’ was established in March 2013 on the territory of Mikrevo nursery of Strumyani Forestry Estate in South-western Bulgaria (41º37´59.6˝ N, 23º11´38.2˝ E). The nursery is situated in the valley of Struma river at 138 m a.s.l. The climate is transitional Mediterranean with mild, warm winter of average minimum temperatures above 0°C and hot summer of maximum average temperatures, measured in July and August, when they exceed 27°C. The average amount of annual precipitations registered in the last 5 years is around 750 mm, with maximum quantity measured in May (above 90 mm). The soil is arable Fluvisol, of low bulk density and slight alkalinity, characterized by good water permeability. Nelder wheel experimental design (Nelder, 1962; Namkoong, 1965) was adopted for the trial plantation, with 11 nearly-square spacings, ranging from 1.0 to 11.5 m², and corresponding to initial densities of 10 000 to 870 plants/ha. The two clones were arranged in alternating spokes and the planting densities varied along the spokes (Fig. 1a, Table 1). Plantation was established on prepared nursery land using standard lignified cuttings (18-20 cm). Irrigations were carried out weekly 8 times during the growth period and nitrogen fertilizer was applied once. More than 95% rooting was achieved and the empty spots were replanted in the autumn of 2013 with standard 1-year-old ramets from the same clones. Around 30% infestation from the wood-boring insect Paranthrene tabaniformis was detected during the first growth period, the entire plantation was cut to the ground for sanitary reasons in the winter of 2013-2014 and was coppiced again in the winter of 2014-2015.

Data collection took place in the winters of 2014-2015 and 2016-2017, and in the autumn of 2017. The trees of 6 spokes (3 spokes per clone) were harvested in 2014-2015 and provided dendromass data from coppiced plants of 2-year-old roots and 1-year-old shoots (Table 1). Sampling of 8 spokes (4 spokes per clone) was done after the forth growth period in 2016-2017, which assured leafless biomass data from coppiced plants of 4-year-old roots and 2-year-old shoots (Table 1). The trees of sixteen spokes (8 spokes per clone) were sampled in the Autumn of 2017 to collect data from coppiced plants of 5-year-old roots and 3-year-old shoots (8 spokes) and from coppiced plants of 5-year-old roots and 1-year-old shoots (8 spokes) (Table 1, Fig. 1b,1c).

Each sample tree was cut at 5 cm maximum stump height. Total length (to the nearest 1.0 cm), basal and breast-height diameters (to the nearest 0.1 cm) of the main shoot and the number of shoots on the stump were measured. Stems and branches of all shoots on each stump were weighted in situ, to the nearest 0.005 kg. One sample of lignified biomass (100-300 g) per spoke was obtained and its fresh weight was measured in the field. The samples were oven-dried at 105°C to constant weight and measured to the nearest 0.001 kg. Proportion of dry mass relative to the fresh weight of a sample was used to estimate the total amount of dry dendromass of each tree in the spoke.
Table 1. Description of the experimental data used to derive the aboveground dendromass models.

<table>
<thead>
<tr>
<th>Clone</th>
<th>Root age+ shoot age</th>
<th>Number of trees</th>
<th>b Spacing, m²</th>
<th>c $d_b$, cm</th>
<th>c $dbh$, cm</th>
<th>c $h$, m</th>
<th>c $w$, kg</th>
<th>c Shoots per stump</th>
</tr>
</thead>
<tbody>
<tr>
<td>‘Agathe’</td>
<td>2+1</td>
<td>33 (11)$^a$</td>
<td></td>
<td>4.9 (2.5-6.7)</td>
<td>3.0 (1.5-4.2)</td>
<td>4.3 (3.0-4.8)</td>
<td>0.705 (0.119-1.561)</td>
<td>5 (2-6)</td>
</tr>
<tr>
<td></td>
<td>4+2</td>
<td>44</td>
<td>1.0, 1.3, 1.6, 2.1, 2.7, 3.4</td>
<td>4.1 (1.5-6.8)</td>
<td>2.5 (0.3-4.3)</td>
<td>3.8 (1.4-5.9)</td>
<td>2.728 (0.064-8.676)</td>
<td>14 (1-30)</td>
</tr>
<tr>
<td></td>
<td>5+1</td>
<td>44</td>
<td>1.4 (0.4-2.2)</td>
<td>0.8 (0-1.2)</td>
<td>1.9 (0.6-2.5)</td>
<td>0.292 (0.008-0.877)</td>
<td>21 (2-43)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5+3</td>
<td>44</td>
<td>5.1 (2.6-8.3)</td>
<td>3.5 (1.6-6.1)</td>
<td>4.9 (2.7-6.4)</td>
<td>4.623 (0.808-11.267)</td>
<td>17 (5-46)</td>
<td></td>
</tr>
<tr>
<td>‘Guardi’</td>
<td>2+1</td>
<td>33 (11)$^a$</td>
<td>4.9 (1.1-6.8)</td>
<td>3.1 (0.3-4.1)</td>
<td>4.2 (1.5-4.9)</td>
<td>0.727 (0.021-1.994)</td>
<td>5 (3-8)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4+2</td>
<td>44</td>
<td>4.6 (2.5-8.4)</td>
<td>2.8 (0.9-5.8)</td>
<td>4.3 (2.0-6.2)</td>
<td>3.643 (0.475-14.210)</td>
<td>14 (4-31)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5+1</td>
<td>44</td>
<td>1.8 (1.2-4.8)</td>
<td>1.1 (0.4-3.0)</td>
<td>2.5 (1.6-4.5)</td>
<td>0.725 (0.045-7.968)</td>
<td>25 (4-57)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5+3</td>
<td>44</td>
<td>6.2 (2.2-9.1)</td>
<td>4.2 (1.2-6.8)</td>
<td>5.4 (2.7-7.3)</td>
<td>5.674 (0.205-25.993)</td>
<td>17 (2-30)</td>
<td></td>
</tr>
</tbody>
</table>

Abbreviations: $dbh$ – breast-height diameter of the main shoot; $d_b$ – basal diameter of the main shoot; $h$ – total height of the main shoot; $w$ – total aboveground dendromass of the stump.

$a$ The sub-set of the trees with recorded shoot number is included in brackets.

$b$ The spacing variants are presented in all Clone-Age combinations (columns 1 and 2).

$c$ Mean and minimum – maximum variable values in brackets are presented.
Model development

According to Sileshi (2014), when using Ordinary Least Squares Regression, the number of the independent variables in the allometric models must consider the sample size used for their parameterization. A minimum of at least 50 measurements is imposed for derivation of one-predictor models and the measurement number should be doubled and tripled with the inclusion of second and third predictor, respectively. The dendromass data available from each investigated clone in our study was sufficient to develop two- and three-factor dendromass models (Table 1). In line with earlier investigations (Menéndez-Miguélez et al., 2013; Stankova et al., 2016), we chose as principal predictor variables the measurements of the main shoot on the stump: basal and breast-height diameters ($d_0$ and $dbh$, respectively) and total height ($h$). We presented them in log-transformed allometric (Eq. 1) and modified constant form-factor (Eq. 2) equation forms and we applied the
method of conditioning (Picard et al., 2012) in order to expand the models by expressing
the slope or the intercept by an additional (secondary) predictor:

\[
\ln w = \ln a + b \ln x
\]  
(1)

\[
\ln w = \ln a + b \ln z^2 h
\]  
(2),

where \( w \) (kg) is the total aboveground dendromass per stump, \( \ln a \) and \( b \) are the
intercept and the slope parameters respectively, \( x \) in Eq. 1 denotes any of the predictors
\( d_0, \) dbh and \( h \) and \( z \) in Eq. 2 denotes either \( d_0 \) or \( dbh. \)

Spacing, root age, shoot age and number of shoots per stump were considered
as the additional predictor. Each data set was divided into classes according to the
levels of the secondary factor (Table 1) and Eqs. 1 and 2 were fitted by classes. Then,
the estimated slopes and intercepts of Eqs. 1 and 2 were plotted against the values of
the classifying variable in order to explore the form of the relationship. Considering
the outcome, we expanded the slope or the intercept of Eqs. 1 and 2 by a function
of the additional factor, formulating from Eqs. 1 and 2 two- and three-factor
biometric models, respectively. Eqs. 1, 2 and the expanded models were then fitted
in log-transformed form to the total data set of each clone and their adequacy was
assessed according to a set of criteria derived from Gadow and Hui (1999), Parresol
(1999), Picard et al. (2012) and Sileshi (2014). Normality of errors was evaluated
according to Shapiro-Wilk analytical test, inspection of the Quantile-Quantile plot
and the values of skewness and kurtosis. Homoscedasticity of errors was judged from
the plot of residuals against predicted values and from White and Breusch-Pagan
analytical tests, while the outliers were controlled in agreement with the requirement
that no more than 10% of the estimated studentised residuals must exceed ± 2. In
case homoscedasticity was not unequivocally proven by all tests, Heteroscedasticity
Consistent Covariance Matrix estimator was applied to ensure the efficiency of the
regression estimates (Long, Ervin, 2000). Regression models were examined for bias by
t-test for mean error equal zero and simultaneous \( F \)-test for slope equal to 1 and zero
intercept of the linear regression relating observed and predicted values. Collinearity
was controlled according to the Condition Number that must obtain values below 30.
Stability of parameter estimates was estimated by the Percent Relative Standard Error,
expressed as the ratio (in percent) between the standard error and the absolute value of
a regression parameter, which must attain values below 25%. To convert the predicted
values to arithmetic, untransformed units, the ratio correction for bias (Snowdon,
1991) was applied. The back-transformed predicted data were also examined for bias
by \( t \)-test for mean error equal zero, 95% confidence interval of errors containing zero
and simultaneous \( F \)-test for slope equal to 1 and zero intercept of the linear regression
relating observed and predicted values. The models were considered unbiased, if at least
2 of the 3 tests proved it. The two- and three-predictor adequate models were grouped
according to the secondary factor they contain and comparison within the groups was
carried out, considering the values of the adjusted coefficient of determination \( (R_{adj}) \),
the root mean squared error (RMSE), Akaike information criterion (AIC) and Akaike
weights. Akaike weights represent the relative likelihood of a model, providing strength
<table>
<thead>
<tr>
<th>Model</th>
<th>Equation</th>
<th>RMSE, kg</th>
<th>$R^2_{adj}$</th>
<th>AIC</th>
<th>AIC weights, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1.1</td>
<td>$\ln w = a_0 + b_1 \text{Age}_1 \ln \text{dbh}$</td>
<td>0.560</td>
<td>0.814</td>
<td>-188.654</td>
<td>100</td>
</tr>
<tr>
<td>M1.2</td>
<td>$\ln w = a_0 + (b_0 + b_1 \text{Age}_1 ) \ln h$</td>
<td>0.690</td>
<td>0.787</td>
<td>-119.463</td>
<td>0</td>
</tr>
<tr>
<td>M1.3</td>
<td>$\ln w = a_1 + a_2 \text{Age}_1 + b_1 \ln h$</td>
<td>0.670</td>
<td>0.800</td>
<td>-129.288</td>
<td>0</td>
</tr>
<tr>
<td>M2.1</td>
<td>$\ln w = a_1 + a_2 \ln SN + b_1 \ln d_0$</td>
<td>0.437</td>
<td>0.923</td>
<td>-233.817</td>
<td>100</td>
</tr>
<tr>
<td>M2.2</td>
<td>$\ln w = a_1 + a_2 SN + b_1 \ln h$</td>
<td>0.592</td>
<td>0.859</td>
<td>-147.024</td>
<td>0</td>
</tr>
<tr>
<td>M3</td>
<td>$\ln w = a_0 + (b_0 + b_1 \text{Age}_2) \ln h$</td>
<td>0.718</td>
<td>0.770</td>
<td>-106.319</td>
<td></td>
</tr>
<tr>
<td>M4.1</td>
<td>$\ln w = a_0 + (b_0 + b_1 \text{Age}_1) \ln (hd_0^2)$</td>
<td>0.529</td>
<td>0.875</td>
<td>-207.089</td>
<td>99.91</td>
</tr>
<tr>
<td>M4.2</td>
<td>$\ln w = a_0 + b_1 \text{Age}_1 \ln (hdbh^2)$</td>
<td>0.553</td>
<td>0.819</td>
<td>-193.112</td>
<td>0.09</td>
</tr>
<tr>
<td>M5</td>
<td>$\ln w = a_0 + b_1 \text{Age}_2 \ln (hdbh^2)$</td>
<td>0.616</td>
<td>0.776</td>
<td>-158.105</td>
<td></td>
</tr>
<tr>
<td>M6</td>
<td>$\ln w = a_1 + a_2 \ln SN + b_1 \ln (hd_0^2)$</td>
<td>0.427</td>
<td>0.927</td>
<td>-240.675</td>
<td></td>
</tr>
</tbody>
</table>

**Abbreviations:** $dbh$ – breast-height diameter of the main shoot; $d_0$ – basal diameter of the main shoot; $h$ – total height of the main shoot; $SN$ – number of shoots on the stump; $\text{Age}_1$ – root age; $\text{Age}_2$ – shoot age; $w$ – total aboveground dendromass of the stump; RMSE – root mean squared error, kg; $R^2_{adj}$ – adjusted coefficient of determination; AIC – Akaike Information Criterion; AIC weights – Akaike weights.
### Table 3. Aboveground dendromass models for clone ‘Guardi’

<table>
<thead>
<tr>
<th>Model</th>
<th>RMSE, kg</th>
<th>R²adj</th>
<th>AIC</th>
<th>AIC weights, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1.1</td>
<td>ln w = a₁ + a₂ Age₁ + b₁ ln d₀</td>
<td>0.558</td>
<td>0.815</td>
<td>-189.755</td>
</tr>
<tr>
<td>M1.2</td>
<td>ln w = a₀ + (b₀ + b₁ Age₁) ln d₀</td>
<td>0.586</td>
<td>0.796</td>
<td>-173.438</td>
</tr>
<tr>
<td>M2.1</td>
<td>ln w = a₁ + a₂ ln Age₂ + b₁ ln dbh</td>
<td>0.684</td>
<td>0.722</td>
<td>-122.157</td>
</tr>
<tr>
<td>M2.2</td>
<td>ln w = a₁ + a₂ ln Age₂ + b₁ ln h</td>
<td>0.689</td>
<td>0.718</td>
<td>-119.944</td>
</tr>
<tr>
<td>M2.3</td>
<td>ln w = a₀ + (b₀ + b₁ Age₂) ln h</td>
<td>0.692</td>
<td>0.716</td>
<td>-118.706</td>
</tr>
<tr>
<td>M3</td>
<td>ln w = a₁ + a₂ ln SN + b₁ ln dbh</td>
<td>0.488</td>
<td>0.855</td>
<td>-202.407</td>
</tr>
<tr>
<td>M4.1</td>
<td>ln w = a₀ + b₁ Age₁ ln (hdbh²)</td>
<td>0.592</td>
<td>0.792</td>
<td>-170.888</td>
</tr>
<tr>
<td>M4.2</td>
<td>ln w = a₁ + a₂ Age₁ + b₁ ln (h₀²)</td>
<td>0.548</td>
<td>0.822</td>
<td>-195.497</td>
</tr>
<tr>
<td>M4.3</td>
<td>ln w = a₀ + (b₀ + b₁ Age₁) ln (h₀²)</td>
<td>0.568</td>
<td>0.808</td>
<td>-183.677</td>
</tr>
<tr>
<td>M5.1</td>
<td>ln w = a₁ + a₂ Age₂ + b₁ ln (hdbh²)</td>
<td>0.682</td>
<td>0.724</td>
<td>-123.542</td>
</tr>
<tr>
<td>M5.2</td>
<td>ln w = a₁ + a₂ Age₂ + b₁ ln (h₀²)</td>
<td>0.702</td>
<td>0.707</td>
<td>-113.564</td>
</tr>
<tr>
<td>M5.3</td>
<td>ln w = a₀ + (b₀ + b₁ Age₂) b₁ ln (h₀²)</td>
<td>0.690</td>
<td>0.717</td>
<td>-119.563</td>
</tr>
</tbody>
</table>

**Abbreviations:** dbh – breast-height diameter of the main shoot; d₀ – basal diameter of the main shoot; h – total height of the main shoot; SN – number of shoots on the stump; Age₁ – root age; Age₂ – shoot age; w – total aboveground dendromass of the stump; RMSE – root mean squared error, kg; R²adj – adjusted coefficient of determination; AIC – Akaike Information Criterion; AIC weights – Akaike weights.
<table>
<thead>
<tr>
<th>Clone</th>
<th>Model</th>
<th>CF</th>
<th>Parameter</th>
<th>$a_0$</th>
<th>$a_1$</th>
<th>$a_2$</th>
<th>$b_0$</th>
<th>$b_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>'Agathe'</td>
<td>M1.1 $w = CF(\exp a_0)dbh^{h A g e_1}$</td>
<td>1.136</td>
<td>Estimate</td>
<td>-0.874</td>
<td></td>
<td></td>
<td>0.369</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>SE</td>
<td>0.068</td>
<td></td>
<td></td>
<td>0.015</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>PRSE %</td>
<td>7.803</td>
<td></td>
<td></td>
<td>4.099</td>
<td></td>
</tr>
<tr>
<td></td>
<td>M2.1 $w = CF(\exp a_1)SN^{a_2}d_0^{b_1}$</td>
<td>1.080</td>
<td>Estimate</td>
<td>-4.347</td>
<td>0.734</td>
<td>2.207</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>SE</td>
<td>0.214</td>
<td>0.065</td>
<td>0.070</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>PRSE %</td>
<td>4.915</td>
<td>8.842</td>
<td>3.155</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>M4.1 $w = CF(\exp a_0)(h d_0^{2}(b_0 + h A g e_1))$</td>
<td>1.010</td>
<td>Estimate</td>
<td>-2.802</td>
<td></td>
<td></td>
<td>0.287</td>
<td>0.124</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>SE</td>
<td>0.118</td>
<td></td>
<td></td>
<td>0.037</td>
<td>0.007</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>PRSE %</td>
<td>4.211</td>
<td></td>
<td></td>
<td>13.065</td>
<td>5.956</td>
</tr>
<tr>
<td></td>
<td>M6 $w = CF(\exp a_1)SN^{a_2}(h d_0^{2})^{b_1}$</td>
<td>1.091</td>
<td>Estimate</td>
<td>-4.538</td>
<td>0.701</td>
<td>0.807</td>
<td></td>
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<td></td>
<td>SE</td>
<td>0.236</td>
<td>0.068</td>
<td>0.026</td>
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<td></td>
<td></td>
<td></td>
<td>PRSE %</td>
<td>5.192</td>
<td>9.710</td>
<td>3.261</td>
<td></td>
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</tr>
<tr>
<td>'Guardi'</td>
<td>M1.1 $w = CF \exp(a_1 + a_2 Age_1)h_0^{b_1}$</td>
<td>1.065</td>
<td>Estimate</td>
<td>-4.712</td>
<td>0.541</td>
<td>2.102</td>
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<td></td>
<td></td>
<td></td>
<td>SE</td>
<td>0.222</td>
<td>0.039</td>
<td>0.081</td>
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<td>PRSE %</td>
<td>4.710</td>
<td>7.262</td>
<td>3.843</td>
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<td></td>
<td>M3 $w = CF(\exp a_1)SN^{a_2}dbh^{b_1}$</td>
<td>1.088</td>
<td>Estimate</td>
<td>-2.835</td>
<td>0.679</td>
<td>1.821</td>
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<td></td>
<td>SE</td>
<td>0.263</td>
<td>0.080</td>
<td>0.063</td>
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<td></td>
<td>PRSE %</td>
<td>9.271</td>
<td>11.718</td>
<td>3.437</td>
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<td></td>
<td>M4.2 $w = CF(\exp(a_1 + a_2 Age_1)(h d_0^{2})^{b_1}$</td>
<td>1.065</td>
<td>Estimate</td>
<td>-5.013</td>
<td>0.515</td>
<td>0.799</td>
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<td>SE</td>
<td>0.226</td>
<td>0.038</td>
<td>0.030</td>
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<td>PRSE %</td>
<td>4.499</td>
<td>7.448</td>
<td>3.762</td>
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**Abbreviations:** CF - correction factor; $dbh$ - breast-height diameter of the main shoot; $d_0$ - basal diameter of the main shoot; $h$ - total height of the main shoot; $SN$ - number of shoots on the stump; $Age_1$ - root age; $Age_2$ - shoot age; $w$ - total aboveground wood mass of the stump; SE - standard error; PRSE % - Parameter Relative Standard Error (%).
of evidence in favor of one model over the other (Wagenmakers, Farrell, 2004; Sileshi, 2014). As a result, adequate two- and three-predictor clone-specific biometric models for the two coppiced black poplar hybrids were derived, allowing reliable aboveground dendromass estimation from various sets of predictors.

**RESULTS**

Both slope and intercept of the examined log-transformed models (Eqs. 1 and 2) revealed linear trends on shoot and root age. Intercepts were linearly related to spacing, while slopes showed logarithmic dependency on spacing. No trends were distinguished between the slopes and the shoot number, while the intercepts exhibited either linear or logarithmic relationship to the number of shoots. All observed trends were considered in formulating the set of biomass models to be examined according to the defined goodness-of-fit criteria.

Ten and twelve adequate allometric dendromass models were derived for clones ‘Agathe’ and ‘Guardi’, respectively (Table 2, 3). Three groups of two-predictor biomass equations were developed for both clones, each group including some of the additional variables root age, shoot age and number of shoots. Three groups of three-predictor models with the same secondary variables were also derived for ‘Agathe’, while either root or shoot age played the role of third predictor in the three-factor models for ‘Guardi’. Adequate models including spacing as an independent variable were not derived.

Four and three best models, which included either root age or number of shoots, were selected for clones ‘Agathe’ and ‘Guardi’, respectively (Table 4). The best three-predictor equations were based on the product between main shoot height and basal diameter of the main shoot, while the best two-predictor regression models involved either basal or breast-height diameter of the main shoot (Table 4). Models including shoot age (M3 and M5 for ‘Agathe’, M2 and M5 for ‘Guardi’) showed inferior in comparison with the other two- and three-predictor biomass equations (Table 2, 3) and therefore they were not considered in the final selection. The clone-specific stump-level models derived in this study explained more than 80% of the variation in the aboveground lignified biomass of the investigated genotypes and obtained root mean squared errors of less than 0.6 kg (Table 2, 3). The two models of best goodness-of-fit statistics for each clone (M4.1, M6 for ‘Agathe’ and M3, M4.2 for ‘Guardi’) are illustrated in Fig. 2, 3.

**DISCUSSION**

We examined planting density as a secondary predictor, because spacing was a principal investigated factor in our Nelder wheel experiment and because biomass can vary with population density. Indeed, biomass of branches, leaves and probably roots, is greatly dependent upon tree architecture and therefore on stand density: considering
trees of equal dimensions (e.g. height, diameter and age), those growing in open stands
will have more branches and leaves than those growing in dense stands (Picard et al.,
2012). Despite this fact, no adequate stump-level dendromass models including spacing
were derived in this study, accounting for problems with normality of errors, unlike the
analogous models with the other additional independent variables. The study of Stankova
et al. (2016) on the dendromass of 4 black poplar hybrids in Northern Bulgaria revealed
that the results on the influence of spacing as a predictor of aboveground dendromass
were not unequivocal and significant relationships were established only for the coppiced
plants of clones ‘BL’ and ‘NNDV’, but not for ‘Agathe’ and ‘I 4551’. The same study
showed that although inclusion of the independent variable ‘Spacing’ significantly
improved the predictability of diameter-only equations, the two-predictor models based
on the stem number attained better goodness-of-fit estimates.

In an investigation on coppiced willows Bergkvist, Ledin (1998) observed that in the
first year after harvest, the average stool weight was strongly reflected by number of shoots

Fig. 2. Observed (dots) and predicted (lines) stump-level dendromass of clone ‘Agathe’.
 a. According to root age, years (M4.1). b. According to shoot number (M6).
Abbreviations: $d_0$ – basal diameter of the main shoot, $h$ – total height of the main shoot

Fig. 3. Observed (dots) and predicted (lines) stump-level dendromass of clone ‘Guardi’.
 a. According to root age, years (M4.2). b. According to shoot number (M3).
Abbreviations: dbh – breast-height diameter, $d_0$ – basal diameter, $h$ – total height of the
main shoot

on the stool. In the second year after harvest, stool weight was still strongly correlated to numbers of shoots per stool, but an increased variability in shoot numbers on stool weight was found. This observation was explained with the increasing within-stool competition, where gradually the few most viable and dominating shoots will survive, leading to a situation where stool weight does not depend as much on shoot number as in the earlier development stages. Laureysens et al. (2003), on the other hand, found that the rate of decay of shoot density is affected by both the genotype and the site conditions. The same authors observed that the number of shoots produced after the second coppicing was much higher than the number produced after the first coppicing, because of the larger diameter of the stumps. However, the number of shoots per stool produced after the second coppicing was not correlated with the number of shoots per stool produced after the first coppicing. Our study also revealed large and variable ranges of shoot number across ages and rotation periods of the coppiced plant data (Table 1, Fig. 2, 3). In spite of this flaw, the generic models, including shoot number, which were derived here, showed the best goodness-of-fit results (Table 2, 3). Their stable parameter estimates (PRSE%<15%, Table 4) and the representativeness of the parameterization data, in terms of rotation turnovers and shoot age, assure the model robustness in future predictions. Our conclusion is in agreement with the finding of Oliveira et al. (2017) that the inclusion of the number of shoots per stool as a predictor variable improves the biomass models under coppice conditions and has a significant influence in terms of uncertainty reduction. Power-form dependencies of aboveground dendromass on shoot number were derived in our study for both clones (Table 4), which is consistent with the multiplicative nature of growth.

The analyzed data sets of our study encompassed plant root age (corresponding also to the age of the stump) from 2 to 5 years and the shoot age ranged from 1 to 3 years. Although adequate models based on both shoot and root age were derived, those including the age of sprouts were of substantially lower predictive power than the models including root age (Table 2, 3). This result is in concordance with the observation by Oliveira et al. (2017) that there is greater uncertainty in the estimation of the allometric model parameters in the year following coppicing, because this growth stage is related to the shoot, rather than to the root age. To develop clone-specific stump-level models for coppiced poplars Valbuena-Castro et al. (2016) and Oliveira et al. (2017) examined power-form models including base diameter and height of the main shoot, and the number of shoots per stool. The authors hypothesized that the rates of relative growth of biomass with respect to these principal predictors depends on tree age and expanded the slope parameters of their models through dummy variables, distinguishing between different root age-shoot age combinations of the coppiced plants. Both studies showed that there is a clear relationship between the estimated value of the slope parameter and the stage of development of the stand, and the predictive power of the expanded models is improved in comparison with the constant-slope models. We also derived adequate dendromass models of good accuracy including root age as a predictor (Table 4). Our results, however, suggested biomass models, which included age variable in either intercept or slope of the power relationships, depending on the clone. Thus, stump age
is accounting for the change in the growth rate of aboveground dendromass regarding breast-height diameter or the product \(hd_2\) of the main shoot of ‘Agathe’, but is reflected in the rate parameter of the intercept of the biomass models of ‘Guardi’ (Table 4).

**CONCLUSIONS**

Stump-level above-ground dendromass models, specific to clones ‘Agathe’ and ‘Guardi’ (\(Populus\ x\ euroamericana\)) in both functional form and parameter estimates, were derived. They are based on principal dimensions of the main shoot on the stump, stump age and shoot number and assure biomass predictions of good accuracy. The models are applicable for estimation of lignified biomass of coppiced plants from these poplar clones, grown at various densities in the transitional Mediterranean climate of south-western Bulgaria and harvested within five years of stump age.

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**REFERENCES**


